

# NEUTRINO NEWS FROM THE LAB AND THE COSMOS

Fermilab, 17-19 October 2002

This workshop will focus on cosmological and terrestrial probes of neutrino masses and mixing, highlighting the implications of recent results, and aiming to bring together members of the particle and astrophysics communities. Particular emphasis will be placed on the interplay and complementarity of cosmological and laboratory based methods of determining neutrino properties, as well as future directions in both areas.

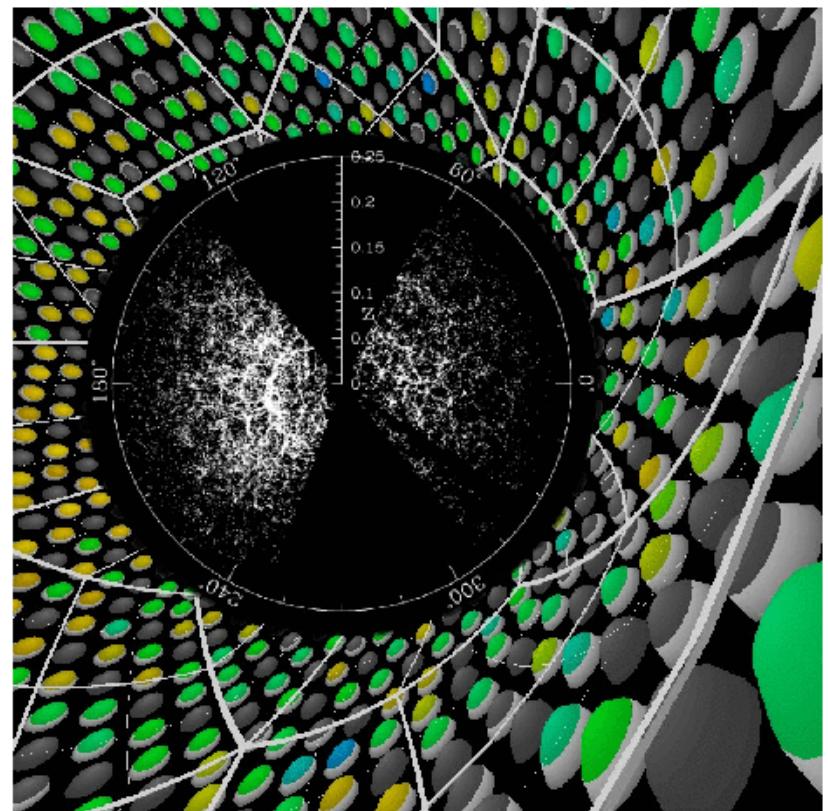
## Topics Include:

- |                             |                               |
|-----------------------------|-------------------------------|
| Large Scale Structure       | Direct Mass Limits            |
| Small Scale Structure       | Solar & Atmospheric Neutrinos |
| Cosmic Microwave Background | Reactor Neutrinos             |
| Big Bang Nucleosynthesis    | Short & Long Baselines        |

## Local Organizing Committee

Kev Abazajian & Nicole Bell  
John Beacom, Janet Conrad, Scott Dodelson, Josh Frieman & Boris Kayser

**Registration and schedule available at:**  
<http://www-astro-theory.fnal.gov/Conferences/NuCosmo/>



Sponsored by Fermi National Accelerator Laboratory

# Cosmological Neutrinos

Number density:

$$n_\gamma = \frac{2\zeta(3)}{\pi^2} T^3 \approx 410 \text{ cm}^{-3}$$

$$n_\nu \approx N_\nu \times \left(\frac{3}{11}\right) n_\gamma \approx 340 \text{ cm}^{-3} \quad (\text{Assuming thermal equilibrium})$$

$$n_\nu \approx 10^{10} n_{\text{baryon}}$$

$$n_\nu \approx 10^{7-9} n_{\text{dark matter}}$$

Neutrino Dark Matter:

$$\Omega_\nu = \frac{\sum m_i n_{\nu i}}{\rho_{\text{crit}}} = \frac{\sum m_i}{93.8 \text{ eV } h^2}$$

# Neutrino Mixing

Neutrino flavors ( $e, \mu, \tau$ ) are not the “true” vacuum neutrinos:

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i ,$$

Simplest case,  $2 \times 2$ :

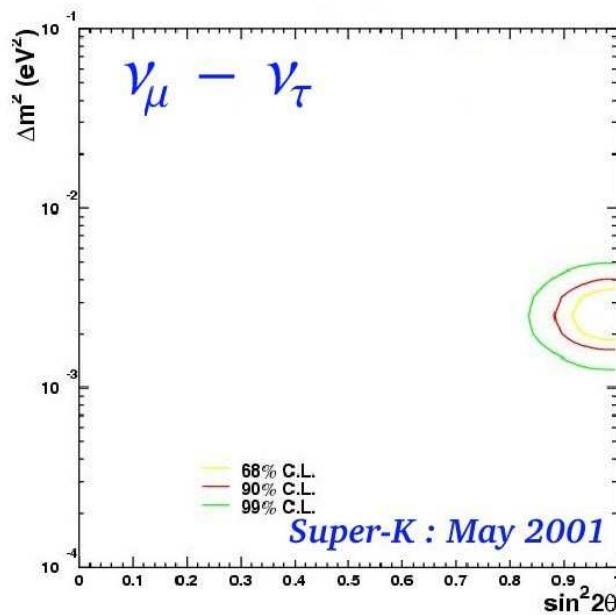
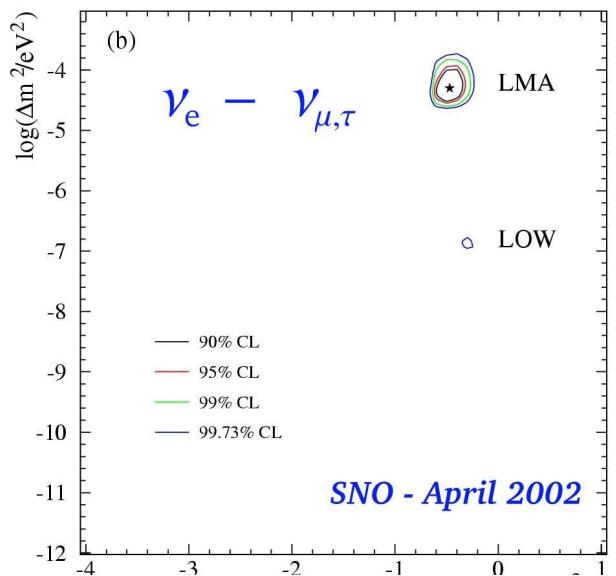
$$\nu_e = \cos \theta_0 \nu_1 + \sin \theta_0 \nu_2 ,$$

$$\nu_\mu^* = -\sin \theta_0 \nu_1 + \cos \theta_0 \nu_2 ,$$

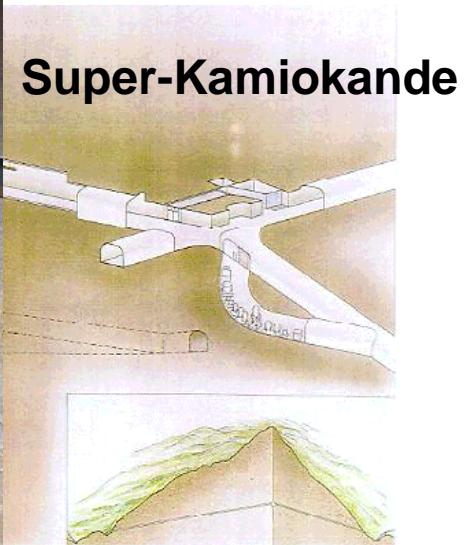
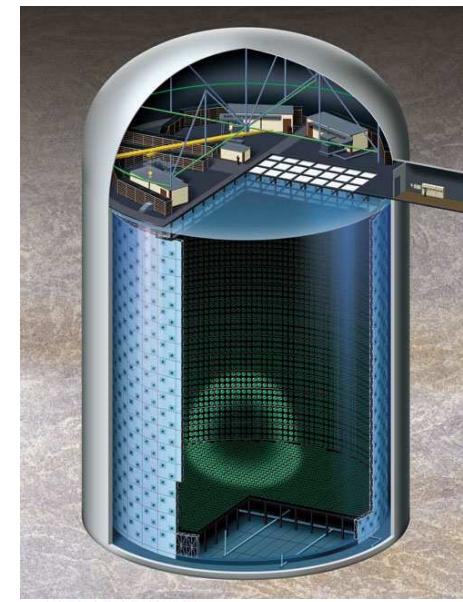
Minimal physical case,  $3 \times 3$ :

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

# Neutrino Oscillations



SNO



# The Emerging Neutrino Mixing Matrix

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i ,$$

$$U = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

Atmospheric results:

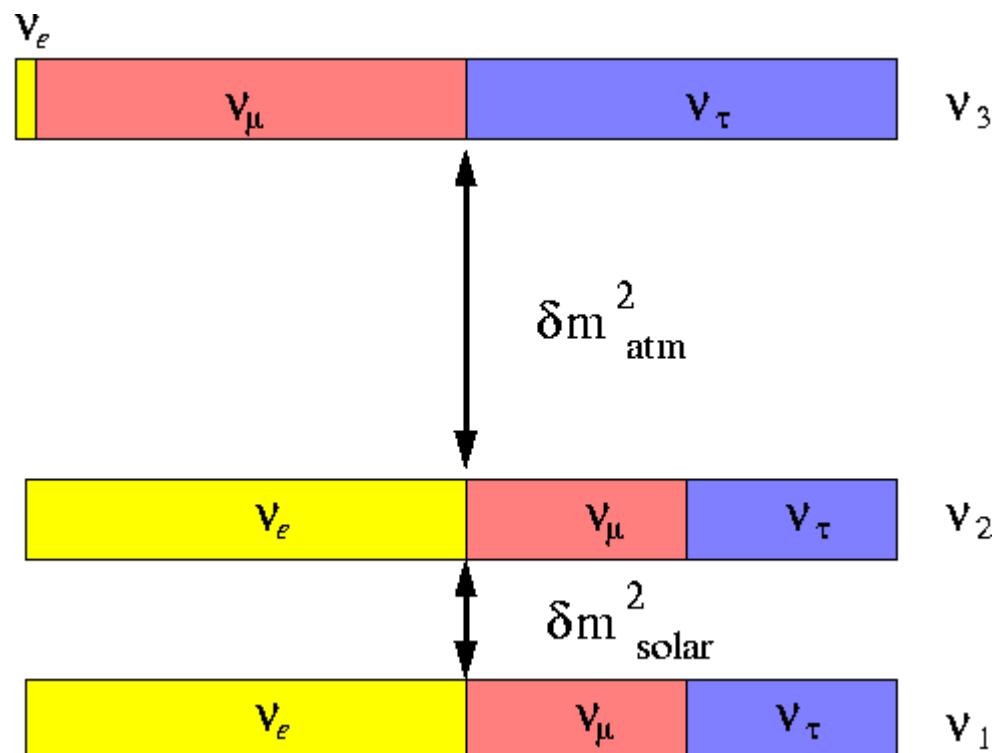
large/maximal  $\theta_{23}$   
→ MINOS/K2K

Solar results:

large  $\theta_{12}$   
→ KamLAND

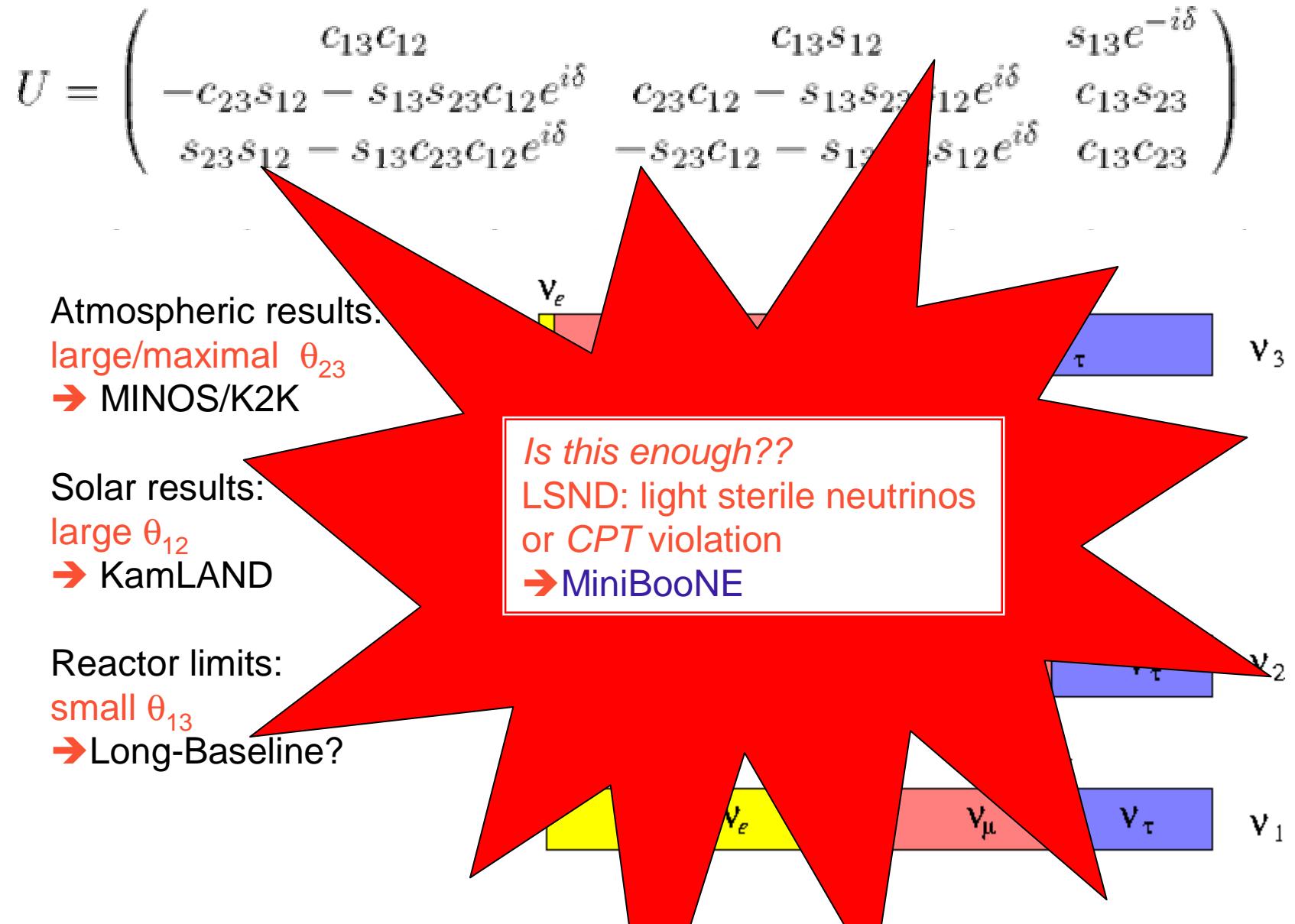
Reactor limits:

small  $\theta_{13}$   
→ Long-Baseline?



# The Emerging Neutrino Mixing Matrix

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i ,$$



## Neutrino Experiment → Cosmology

the overall mass scale of neutrinos  
(small  $\delta m^2$ 's)

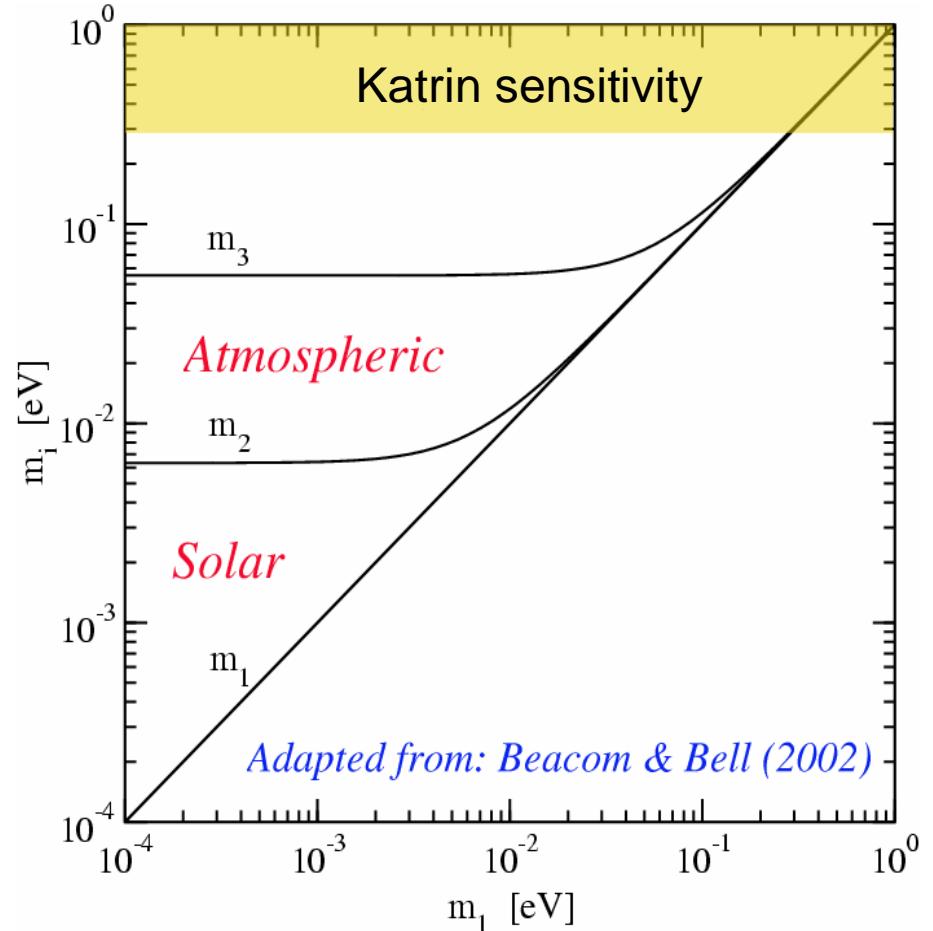
- Lower limit:

$$m_\nu \geq \sqrt{\delta m_{atm}^2} \approx 0.05 \text{ eV}$$

- Upper limit:

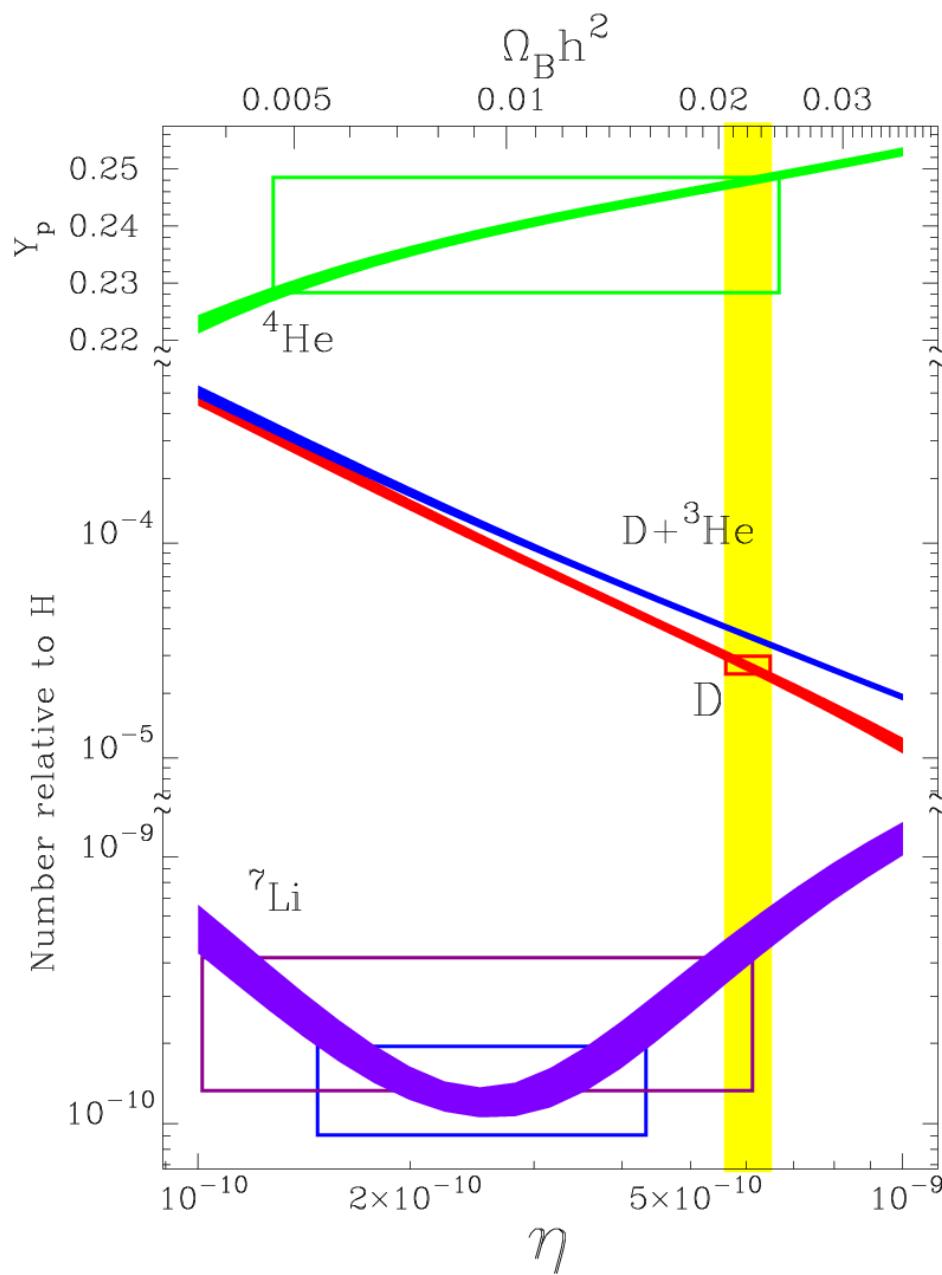
$$\langle m_{\nu_e} \rangle < 3 \text{ eV}$$

( ${}^3\text{H}$  endpoint)



*Extreme effects of very massive active neutrinos (decay, etc.) in the early universe can be safely ignored*

# Cosmology → Neutrino Physics



## Big Bang Nucleosynthesis

Concordance of light element abundances with standard theory

→ Gives precision accounting of the components (matter and energy) of the universe at early times  $\sim 1$  sec!

→ Constraining new neutrino physics

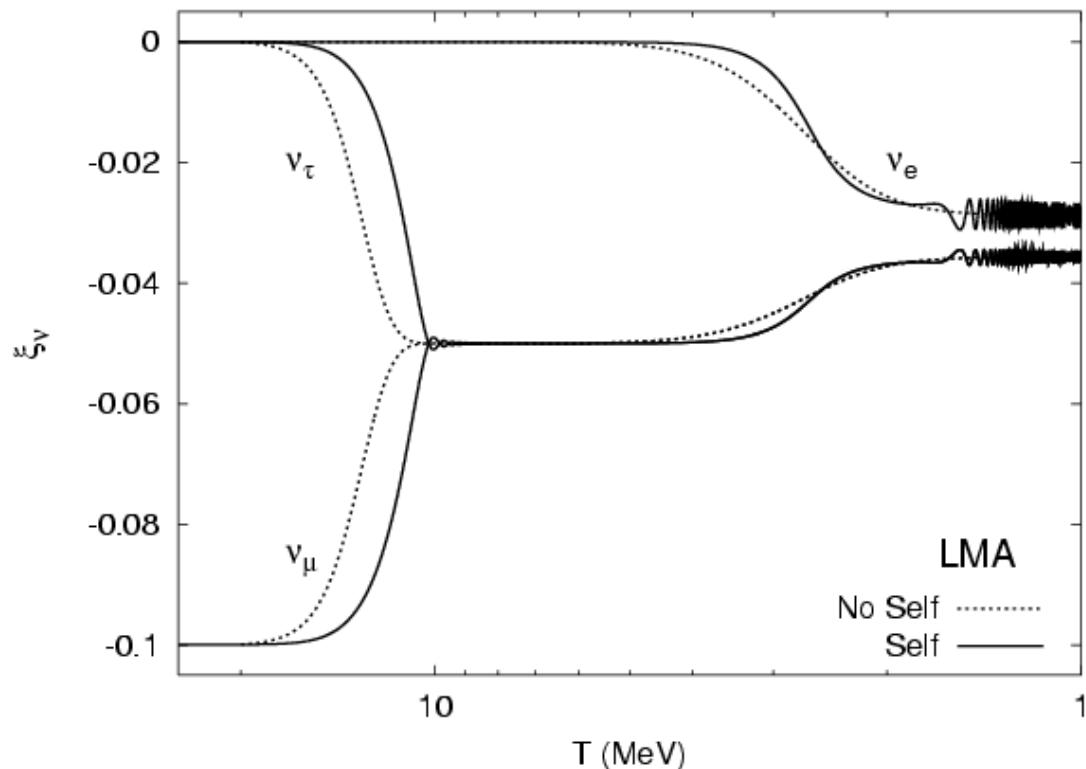
# Neutrino Experiment → Cosmology

number density of neutrinos

Generally:

$$n_{\nu} = \left( \frac{3}{11} \right) \frac{2\zeta(3)}{\pi^2} T^3 F_2(\xi)$$

$$n_{\nu} \approx 113 \text{ cm}^{-3} F_2(\xi)$$



LMA solar + maximal ATM

→ Any chemical potential will alter the  ${}^4\text{He}$  abundance.

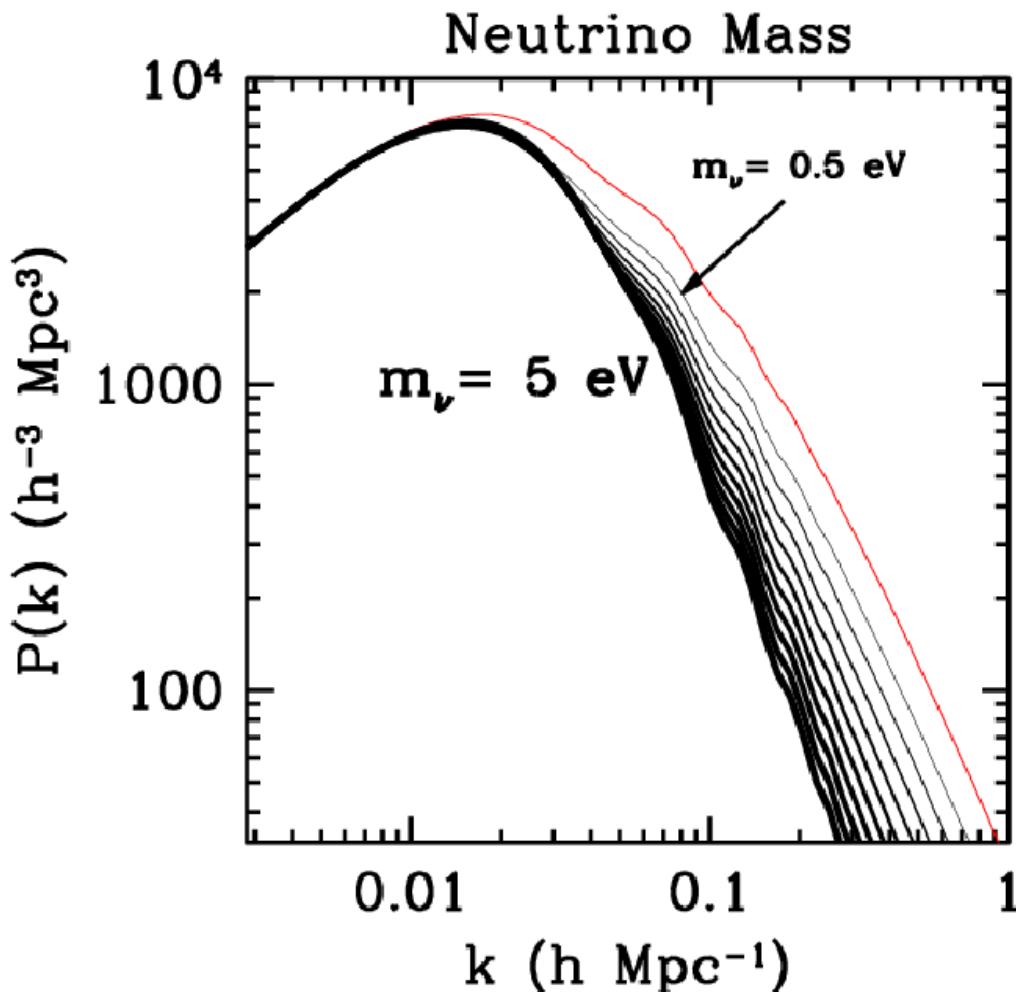
$$\xi \ll 1$$

$$n_{\nu} \approx 113 \text{ cm}^{-3} \text{ flavor}^{-1}$$

$$\Omega_{\nu} = \frac{\sum m_i n_{\nu i}}{\rho_{crit}} = \frac{\sum m_i}{93.8 \text{ eV } h^2}$$

(Dolgov et al; KA, Beacom, Bell; Wong 2002)

## Cosmology → Neutrino Physics



- Neutrino experiment: mass splittings & cosmological number density
- 2dF Galaxy Redshift Survey: upper mass limit  $\sum m_\nu < 1.8 \text{ eV} \Rightarrow m_\nu < 0.6 \text{ eV}$

Measurements of the spectrum of fluctuations:

- galaxy surveys
  - cosmic shear (weak lensing)
  - Lyman- $\alpha$  forest
  - CMB
  - galaxy cluster abundances
- Give precision accounting of the components (matter and energy) of the universe

$$\Omega_m, \Omega_{\text{dark energy}}, \Omega_{\text{total}}$$

$$\Omega_\nu = \frac{\sum m_i n_{vi}}{\rho_{crit}} = \frac{\sum m_i}{93.8 \text{ eV } h^2}$$

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## The Nobel Prize in Physics 2002

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"



photo PRB

**Raymond Davis Jr.**

● 1/4 of the prize  
USA

University of  
Pennsylvania  
Philadelphia, PA,  
USA

b. 1914



photo PRB

**Masatoshi Koshiba**

● 1/4 of the prize  
Japan

University of  
Tokyo  
Tokyo, Japan

b. 1926



photo NASA/CXC/SAO

**Riccardo Giacconi**

● 1/2 of the prize  
USA

Associated  
Universities Inc.  
Washington, DC,  
USA

b. 1931  
(in Genoa, Italy)

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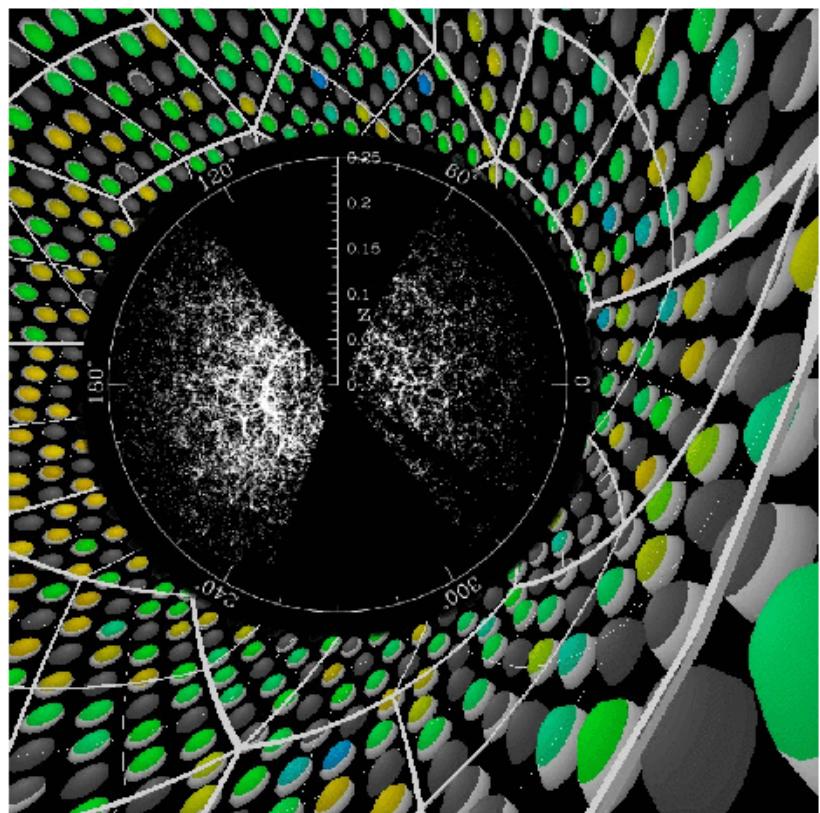
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